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The Impact of High Pressure Cluster Environment on the X-ray Luminosity of Coma Early-type Galaxies

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Abstract. We present an observational study of the L_X vs $L_B\sigma^2$ relation for early-type galaxies in the Coma cluster based on the XMM-Newton survey data. Compared to a similar relation for a sample dominated by field early-type galaxies, the Coma cluster galaxies show a flatter slope. Our calculations show that adiabatic compression produces a flattening in the L_X vs $L_B\sigma^2$ relation that is in remarkable agreement with the observed effect. Our scenario is further supported by the observed compactness of the X-ray emission of Coma galaxies.

Key words. clusters: individual: Coma — X-rays: galaxies — X-rays: ISM

1. Introduction

X-ray emission from early-type galaxies has been subject of investigations and theoretical modeling ever since its discovery with the Einstein telescope (Forman, Jones, Tucker 1985). The X-ray emission appears in part to be diffuse in nature and to originate in the galaxy hot interstellar medium (ISM); and in part to be due to a population of X-ray point sources, namely low mass X-ray binaries characterized by a hard spectrum. In fact, the X-ray spectra are typically well fit with a two-component model: a soft $\sim$1 keV thermal component for the hot ISM and and a hard $\sim$1.4 photon index power law contribution for the point sources (Irwin et al. 2003). The latter component is systematically more important for fainter objects (Matsushita 2001).

The temperature of the ISM is proportional to the stellar velocity dispersion and, although with some scatter, the coefficient of proportionality is close to unity. In fact, the main energy input to the hot ISM is thought to be due to thermalization of kinetic energy associated with stellar mass loss, in addition to energy input from explosions of SN Ia (Mathews 1989; Ciotti et al. 1991; David et al. 1991). However, in some cases the galaxy ISM is found to be considerably hotter than the stellar velocity dispersion would indicate, as for example in the case of galaxies in the center of massive groups (Brown & Bregman 1998; Matsushita 2001).

In this respect the relation between X-ray and optical properties is important in order to understand the processes regulating the evolution of the hot gas. In fact, early on it was realized the existence of a correlation between the X-ray and the blue band stellar luminosity. Both the log-slope of the correlation and the significant scatter about it are physically meaningful and need to be properly understood and modeled.

In addition, X-ray and optical properties of ellipticals are used in combination for testing different scenarios of galaxy formation. Thus, Kodama & Matsushita (2001) used the continuity of optical properties across X-ray extended and compact early type galaxies to show that, if the different X-ray emission properties of the two classes are related to the structure of the underlying dark matter potential, then the formation of stars in these galaxies must predate the epoch when the potential structure was established.

In this *Letter* we address the impact of high pressure cluster environment on the diffuse X-ray emission of early type galaxies. For the purpose we use the recent X-ray catalog of Coma cluster galaxies based on XMM-Newton survey and presented in Finoguenov et al. (2004a) and compare with the results reported in Matsushita (2001). In addition, we concentrate on X-ray compact galaxies as defined in Matsushita (2001). We find that X-ray emission from early-type galaxies in Coma is systematically higher when compared to their counterparts in the field or in loose groups, such as those presented in Matsushita (2001). We show that compression induced by the high pressure ICM is sufficient to reproduce the observed effect and point out that such environmental effects should be taken into account when modeling the X-ray properties of these galaxies.

This *Letter* is structured as follows. In §2 we describe the data; in §3 we plot L_X vs $L_B\sigma^2$ for Coma galaxies illustrating the main result of this letter; in §4 we attempt an interpretation of the observational results by estimating the effect of intracluster gas on X-ray luminosity; we conclude with §5. We use H_0 = 70 km s^{-1} Mpc^{-1} throughout.

2. X-ray data

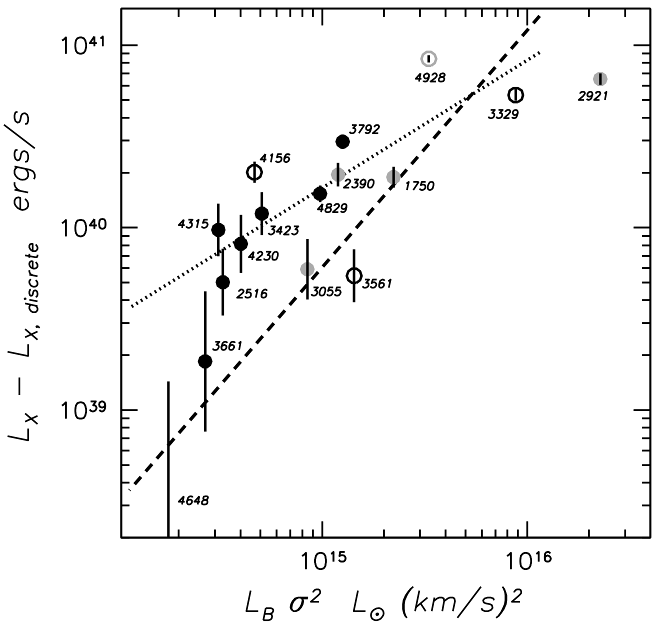

Fig. 1. $L_{\rm X} - L_{\rm B}\sigma^2$, using measurements of σ from Jørgensen (1999). Contribution from discrete point sources has been subtracted (see text for details). Open symbols denote the sources also identified as FIRST (radio) sources. Grey points correspond to boxy ellipticals and black to disky. Dashed line is a fit to a similar relation for the field ellipticals (Matsushita 2001) and dotted line is the expected curve if diffuse X-ray emission balances the energetic input from the stellar mass loss, that is $\propto \dot{M}_{*}\sigma^2 \propto L_{\rm B}\sigma^2$ (e.g. Ciotti et al. 1991). This curve also represents the flatter relation expected as a result of the effects of ICM pressure (see §4). Luminosities are calculated assuming a 100 Mpc distance to the Coma cluster, appropriate for H_0 = 70 km s^{-1} Mpc^{-1}. Numbers on the plot show the denumerations of galaxies in the catalog of Godwin et al. (1983).

XMM-Newton survey of the Coma cluster (Briel et al. 2001) covered a region of 1.89 square degrees. In Finoguenov et al. (2004a) over six hundred sources with extent less then 10″ have been detected, sixty of which were identified with galaxies that are spectroscopically confirmed members of the Coma cluster. For the purpose of this paper we have selected a subsample of early-type galaxies, for which measurements of the velocity dispersion exists in the literature (Jørgensen 1999). For these galaxies, we have also found a measurement of the structural parameter, which we further use to divide the sample into disky and boxy ellipticals (Saglia et al. 1993; Mehlert et al. 2000).

Current AGN activity may influence the X-ray luminosity in galaxies (Finoguenov et al. 2004b), although this should not be the case for our sample as its members are exclusively characterized by thermal colors (Finoguenov et al. 2004a). Past AGN activity can still be revealed by the presence of radio emission. Thus, we have marked with a special symbol the galaxies in our sample that are also found in the FIRST survey (Becker et al. 1995). The sample we will consider in the following includes the Coma cluster galaxies with the following denumerations in the catalog of Godwin et al. (1983; GMP): 2390, 2921, 3055, 3329, 3423, 3792, 4156, 4230, 4315, 4829, 4928, 1750, 2516, 3561, 4648, 3661. For each galaxy we estimate the X-ray luminosity in the 0.5–2 keV band from the diffuse component. The contribution from the unresolved point sources has been subtracted using estimates based on the well resolved (by Chandra) observations of this population in the nearby elliptical M84 (Finoguenov & Jones 2001). A correction for the aperture of XMM-Newton source extraction, was also introduced as described in Finoguenov et al. (2004a). For most but the two X-ray faintest sources, subtraction of the unresolved component introduces no difference in the inferred flux. In part, this is caused by the small extent of the diffuse X-ray emission of Coma ellipticals (Vikhlinin et al. 2001), which results in a thermal to unresolved point source flux ratio that is higher in the inner regions of these galaxies. In fact, in Coma galaxies the spatial distribution of the X-ray emission from LMXB is similar to the stellar light and extends out to four effective radii, while the diffuse X-ray emission is more centrally concentrated, typically within an effective radius.

3. $L_{\rm X}$ vs $L_{\rm B}\sigma^2$ for Coma cluster early-type galaxies

In Fig.1 we plot the diffuse X-ray luminosity versus $L_{\rm B}\sigma^2$, the product of the stellar blue band luminosity times its central velocity dispersion. The sample is the one discussed in the previous section. The main result of this *Letter* is the measurement of a significantly flatter slope in the plotted relation with respect to the one reported for field galaxies (Matsushita 2001).

Matsushita (2001) already found a correlation between $L_{\rm X}$ (using a slightly different energy band, 0.2–2 keV) and $L_{\rm B}\sigma^2$ for a sample of compact early-type galaxies including 30 field galaxies and 12 cluster galaxies (3 members of Fornax cluster plus 9 members of Virgo cluster). Galaxies with emission extending beyond four effective radii were excluded from her study. As shown in Fig. 1 Coma galaxies also follow a $L_{\rm X} - L_{\rm B}\sigma^2$ relation but with a significantly different slope. Chandra observations already reported lower X-ray luminosities for the two central ellipticals (Vikhlinin et al. 2001), consistent with our plot. In addition, here we show that numerous other galaxies exhibit *higher* X-ray fluxes than expected from the relation presented in Matsushita (2001), a feature that was not identified in previous studies.

We note the presence of significant scatter in the plot in Fig. 1. In order to investigate its origin, we have inspected the X-ray images of the sample galaxies, presented in Finoguenov et al. (2004a). The emission of all the sources is within two effective radii, so they all fulfill the compactness criterion of Matsushita. However, some of the Coma galaxies are much more compact than that, e.g. the extent of the emission in the GMPs 2921 and 3329 is a few percent of the effective radius (Vikhlinin et al. 2001), which we denote as ultracompact. Other ultracompact X-ray sources, include GMPs 2921, 3329, 4156, 2390, 4829, 3055, 3423, 4315, 4230, 3792. Their emission appears nearly point-like and limits on the spatial extent are lower than half the effective radius. With exception of GMP 3055, which has a factor of two lower X-ray flux and GMP 4156, which has a factor of two higher X-ray flux, all of them are found on the main relation for Coma cluster galaxies. GMP 3792 has a secondary point source associated with another galaxy, which explains its factor of 1.5 higher luminosity. Some galaxies exhibit

extended emission or/and emission strongly displaced from the center. These are GMPs 2516, 1750, 3561, 3661, 4648. All of them are found on the relation for field ellipticals. This evidence may suggest that the galaxies departing from the main relation are experiencing some disruption such as gas stripping effects. Unlike two bright cluster galaxies (BCG)in Coma (GMPs 3329 and 2921), BCG of the infalling cluster, GMP 4928 (NGC 4839), has not been separated from the surrounding gas and although it also exhibits an ultracompact source, we tentatively ascribe it to galaxies with diffuse emission.

Table 1. Parameter values for $L_{\rm X}-L_{\rm B}\sigma^2$ relation†

sample	A	B	A$^\flat$	B$^\flat$
all	$1.05^{+0.01}_{-0.01}$	$1.13^{+0.29}_{-0.23}$	$1.12^{+0.36}_{-0.30}$	$1.12^{+0.40}_{-0.34}$
–GMP4928	$1.00^{+0.02}_{-0.02}$	$1.08^{+0.30}_{-0.23}$	$1.07^{+0.39}_{-0.29}$	$1.07^{+0.45}_{-0.38}$
–radio	$1.03^{+0.07}_{-0.05}$	$1.16^{+0.28}_{-0.22}$	$1.17^{+0.64}_{-0.36}$	$1.19^{+0.70}_{-0.48}$
radio	$1.32^{+0.48}_{-0.43}$	$0.93^{+0.61}_{-0.38}$	unconstrained	
disky	$1.33^{+0.31}_{-0.18}$	$1.40^{+0.47}_{-0.33}$	$1.56^{+2.35}_{-0.54}$	$1.43^{+0.90}_{-0.62}$
boxy	$1.17^{+0.18}_{-0.18}$	$0.78^{+0.16}_{-0.14}$	unconstrained	
ultracompact	$1.63^{+0.01}_{-0.01}$	$0.48^{+0.01}_{-0.01}$	$1.62^{+0.24}_{-0.26}$	$0.47^{+0.14}_{-0.18}$
–ultracompact	$0.75^{+0.01}_{-0.01}$	$1.71^{+0.07}_{-0.06}$	unconstrained	

† $L_{\rm X}=A\times10^{40}$ergs $s^{-1}(\frac{L_B\sigma^2}{10^{15}L_\odot{\rm km\ s^{-1}}})^B$. Errors are given at 68% confidence level.

$^\flat$ Bootstrap method is used to estimate the mean and the variance.

In order to quantify the measured effect and possible variations associated with particular properties of the galaxies in our sample, in Tab.1 we present results from a linear regression analysis in $log(L_{\rm X})-log(L_{\rm B}\sigma^2)$ space of the relation $L_{\rm X}=A\times10^{40}$ ergs s^{-1} $(\frac{L_{\rm B}\sigma^2}{10^{15}L_\odot{\rm km\ s^{-1}}})^B$. Our method allows for errors in both variables and intrinsic scatter (Akritas & Bershady 1996). We use the bisector method to determine the best-fit parameters (Isobe et al. 1990). The resulting values are reported in columns (2–3) of Tab.1. To estimate the effect of selection of data points we perform an additional analysis, calculating the mean and the dispersion in the best-fit values, obtained through 10000 bootstrap realizations. These values are reported in columns (4–5) of Tab.1. The samples we consider, listed in the first column of Tab.1, correspond to: the complete set of galaxies; the same excluding GMP 4928; the same excluding galaxies with identified radio counterpart; the set of disky galaxies; the set of boxy galaxies; ultracompact (located well within half the effective radius) X-ray emission; diffuse X-ray emission. Comparing the results for the different samples should reveal how the studied relation changes for, and is affected by, galaxies with different properties. Removing GMP 4928 has no effect on our results which are determined by the bulk of the studied objects. Similarly, results are not significantly affected by galaxies with identified radio counterpart. Contrary to their position on the $L_{\rm X}-L_{\rm B}$ relation (Bender et al. 1989), disky galaxies are not underluminous in the sense of $L_{\rm X}-L_{\rm B}\sigma^2$, in agreement with Kodama & Matsushita (2000). However, disky and boxy galaxies yield somewhat different slope, with disky galaxies exhibiting a steeper relation. However, bootstrap realizations indicate that this result could be reproduced by selection of systems. Galaxies with ultracompact emission exhibit slope flatter than a relation for the field ellipticals in Matsushita (2001) at the highest significance.

In the following, we will analytically derive the influence of the external pressure on the observed slope of the $L_{\rm X}-L_{\rm B}\sigma^2$ relation.

4. Impact of intracluster pressure

The X-ray emitting gas in elliptical galaxies is expected to be in conditions of hydrostatic equilibrium so that a given gas pressure arises in response to, and to balance out, the pull of the gravitational force.

However, within the environment created by a much more massive structure, such as a rich cluster of galaxies, the pressure can be quite higher that required by the conditions of hydrostatic equilibrium. Therefore, the galaxy interstellar gas can be further compressed. A direct confirmation of the pressure equilibrium between the ISM of two Coma ellipticals and the ICM is presented in Vikhlinin et al. (2001). If the compression is adiabatic, entropy is conserved and as a result of a pressure increment, $\Delta P\geq0$, the following thermodynamic variations are expected to take place

$$P\longrightarrow P(1+\Delta P/P) \tag{1}$$
$$\rho\longrightarrow \rho(1+\Delta P/P)^{1/\gamma} \tag{2}$$
$$T\longrightarrow T(1+\Delta P/P)^{(\gamma-1)/\gamma} \tag{3}$$

where P,ρ,T are pressure, density and temperature respectively, γ is the gas adiabatic index, $\Delta P=P_{\rm ICM}-P$, and $P_{\rm ICM}$ is the external pressure which in this specific case corresponds to the intracluster pressure of Coma cluster.

If the X-ray luminosity were simply due to thermal bremsstrahlung emission, then

$$L_{\rm X}\propto\rho T^{1/2}M_{\rm gas}\longrightarrow L_{\rm X}(1+\Delta P/P)^{(\gamma+1)/2\gamma}. \tag{4}$$

where M is the galactic interstellar gas mass. However, X-ray emission in the 0.5–2 keV band of XMM-Newton EPIC pn as well as 0.2–2 keV band of ROSAT PSPC detectors is dominated by L-shell iron emission lines. It turns out that due to changes in the ionization equilibria, for metallicities of order $0.1-0.5$ solar, a temperature increase does not affect the emitted X-ray power in the selected energy band. More precisely, the flux slightly increases for metallicities ~0.1 but decreases for metallicities ≥0.5. The ISM metallicities of all these galaxies are not precisely known, but are expected to be in this range (Finoguenov & Jones 2000, 2001), as measured for two brightest Coma ellipticals (Vikhlinin et al. 2001). So for the current calculation we will assume that the flux is unchanged under temperature variations. Thus, the changes in the X-ray luminosity induced by compression are simply those due to the density enhancements to the first power

$$L_{\rm X}\longrightarrow L_{\rm X}(1+\Delta P/P)^{1/\gamma}\propto L_{\rm X}T^{-1/(\gamma-1)} \tag{5}$$

where in the last passage we have used the $P-T$ relation for an adiabatic gas.

In order to infer the change in the $L_{\rm X}-L_{\rm B}\sigma^2$ relation we need to somehow express the quantity $L_{\rm B}\sigma^2$ in terms of

some thermodynamic variable, like the temperature for example. According to scaling relations for virialized systems, the velocity dispersion should be of order of the virial temperature T. In addition we expect that the B-band luminosity be proportional to the stellar mass loss, that feeds the X-ray luminosity of ellipticals (Mathews 1989); if the latter is a fixed fraction (proportional to) the halo mass, then invoking again scaling relations we obtain $L_{\rm B} \propto T^{3/2}$ and $L_{\rm B}\sigma^2 \propto T^{5/2}$.

Combining this result with Eq. (5), we find

$$L_{\rm X} = (L_{\rm B}\sigma^2)^{\alpha} \longrightarrow (L_{\rm B}\sigma^2)^{\alpha-\frac{2}{5(\gamma-1)}}. \tag{6}$$

where α is the slope in absence of ICM compression effects, like the case measured by Matsushita (2001). For an adiabatic index $\gamma = 5/3$ the slope of the above relation is expected to flatten by an amount $3/5$. The flattened curve as predicted by this calculations is plotted in Fig. 1 as a dotted line and given the simplicity of our model the match to the observed effect is quite good.

5. Discussion and conclusions

In this paper we have studied a sample of early type galaxies from Coma cluster. We have shown that the diffuse X-ray emission of such galaxies when plotted against the blue band stellar luminosity times the stellar central velocity dispersion, follows a flatter curve than similar galaxies in the field do (Matsushita 2001). Further, we have shown that, starting from the $L_{\rm x}$ vs $L_{\rm B}\sigma^2$ relation measured by Matsushita (2001), we can recover the flatter relation for the galaxies in Coma cluster by accounting for the effects of adiabatic compression from the hot ICM.

$L_{\rm B}\sigma^2$ represent the maximum energy input associated with stellar mass loss (Matsushita 2001, Ciotti et al. 1991). According to our calculations the line $L_{\rm X} = 3.2 \times 10^{40}$ ergs s^{-1} $\alpha_{\rm x}$ $\frac{L_{\rm B}\sigma^2}{10^{15}\, L_\odot\, ({\rm km\ s}^{-1})^2}$ in the $L_{\rm X} - L_{\rm B}$ diagram, where $\alpha_{\rm x} \simeq 0.4$ is the ratio of 0.5–2 keV X-ray to bolometric emissivity, corresponds to the maximum X-ray emissivity if indeed stellar mass loss is the energy source that feeds the diffuse X-ray emission. In fact, this line roughly draws an upper envelope for the compact sources in Matsushita's (2001) sample. Interestingly, Coma galaxies reported in this letter tend to lay on such curve. This is consistent with the above idea about the source of energy for the X-ray emission. In this respect, it is worth pointing out that numerous Coma galaxies in our sample can be characterized as having a "ultracompact" X-ray structure and, therefore, according to Matsushita, should be underluminous. Despite this, they also clump near the same theoretical curve based on the assumption that the heating of the galaxies ISM is supplied by the stellar mass loss.

It is worth pointing out that in deriving the X-ray scaling relations for the early-type galaxies, we have not included the contribution of SN Ia to gas heating (Ciotti et al. 1991). However, according to recent stellar age determinations, field early-types have a systematically younger age than the cluster population (e.g. Terlevich, Forbes 2002), which implies a stronger SN Ia activity there (Greggio & Renzini 1983). Thus, if SN Ia played a dominant role in determining the X-ray luminosity of early-types, we would expect cluster galaxies to exhibit lower luminosities, which is not observed.

There are theoretical arguments and observational evidence supporting the idea that ram pressure stripping is one of the principal mechanisms affecting the morphology of X-ray galaxies (e.g. Vollmer et al. 2001, Bravo-Alfaro et al. 2001, Finoguenov et al. 2004a; see also Finoguenov et al. 2004c). Gas stripping, however, implies a reduction of gas content of the cluster galaxies which, in absence of other effects, leads to a decrease of the level of X-ray emission. We have demonstrated that in fact X-ray emission in Coma cluster galaxies is on average higher than in their field counterparts with similar stellar properties. This is sensibly explained by ICM compression as outlined in the previous Section, which, therefore, adds to the wide variety of processes that affect the evolution of X-ray galaxies.

Finally, as Coma galaxies are more luminous than those in the field because of the high outer pressure, some galaxies in the field may likewise be underluminous, because they expanded when the energy input from mass loss is sufficiently high in comparison to the depth of their potential well. It will be interesting to further investigate this possibility in the future especially in connection with the new developments in the study of low-sigma early-type galaxies (Burkert & Naab 2003).

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